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RESEARCH MEMORANDUM

FLIGHT DETERMINATION OF THE EFFECTS OF WING VORTEX
GENERATORS ON THE AERODYNAMIC CHARACTERISTICS
OF THE DOUGLAS D-558-I AIRPLANE

By De E. Beeler, Donald R. Bellman, and
John H. Griffith

Langley Aeronautical Laboratory
Langley Field, Va.

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RESEARCH MEMORANDUM

FLIGHT DETERMINATION OF THE EFFECTS OF WING VORTEX
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SUMMARY

Tests were made of the Douglas D-558-I airplane to determine the effect of wing vortex generators on some of the typical undesirable handling characteristics such as buffeting, lateral unsteadiness, change in trim, and loss in control effectiveness which have occurred on present-day aircraft flying at supercritical speeds. An arbitrary size, shape, and location of the generators were selected and the investigation was initiated to determine what benefits might be derived from the installation and whether further investigations would be warranted.

The use of the vortex generators resulted in a reduction of separated regions over the wing at Mach numbers greater than 0.85 for level flight. At higher normal-force coefficients for Mach numbers greater than 0.85, regions of separation and forward movement of the shock were reduced. The buffet boundary and wing-dropping tendency were delayed approximately 0.05 in Mach number for level flight; however, no change in the small-amplitude oscillation was detected. The pilot reported the buffeting to be appreciably reduced during flights penetrating the buffet region for lift coefficients below the stall. No detrimental effects on the longitudinal and lateral control characteristics were encountered for the flight conditions investigated. The drag of the airplane was increased by the use of the generators.

INTRODUCTION

Present-day airplanes flying at supercritical speeds have demonstrated the effects of compressibility in the form of buffeting, lateral unsteadiness, change in trim, and loss in control effectiveness. In the course of flight testing the research airplanes, modifications to the

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specific configurations of these airplanes have been considered for the purpose of reducing the magnitudes and/or delaying the effects of compressibility which are objectionable from the handling and the structural standpoint. Based on results of reference 1, an investigation was made at the NACA High-Speed Flight Research Station at Edwards Air Force Base, Calif., to determine the effect of wing vortex generators on the handling and buffeting characteristics of the Douglas D-558-I research airplane.

The D-558-I is capable of penetrating the buffet region to some degree and experiences a lateral unsteadiness in level flight, an abrupt lateral trim change (reference 2), and a loss in control effectiveness.

This paper presents the results of flight tests to determine the effect of the vortex generators on some of the forementioned undesirable characteristics of the airplane.

SYMBOLS

C_{N_A}	airplane normal-force coefficient (nW/qS)
C_D	drag coefficient (D/qS)
$C_{m_{\bar{c}}/4}$	pitching-moment coefficient about wing quarter chord, (stall moment is positive)
$\bar{c}/4$	one-quarter of M.A.C., feet
D	total airplane drag, pounds
F_a	aileron force, pounds
M	Mach number
M.A.C.	mean aerodynamic chord
P	pressure coefficient $\left(\frac{p_1 - p_o}{q}\right)$
ΔP_T	loss in total head, free-stream impact pressure minus local impact pressure
S	wing area, square feet
V	true velocity, feet per second
W	weight of airplane, pounds

b	wing span, feet
c_w	wing chord, feet
y/c	ratio of height above mean chord line to section chord
i_t	stabilizer incidence, degrees
n	normal acceleration
p	rolling velocity, radians per second
p_o	free-stream static pressure, pounds per square foot
p_l	local static pressure, pounds per square foot
q	free-stream dynamic pressure, pounds per square foot
δ_a	aileron deflection, degrees
δ_e	elevator deflection, degrees

TEST EQUIPMENT AND PROCEDURE

Airplane

The Douglas D-558-I airplane used for these tests is a single-place low-wing monoplane powered by a General Electric TG-180 turbojet engine. The center of gravity was located at 23.34 percent of the mean aerodynamic chord and the gross weight at take-off was 10,610 pounds. Table I lists the more pertinent physical characteristics of the airplane and figures 1 and 2 are a three-view sketch and a photograph of the airplane, respectively.

Vortex Generators

The vortex generators were made from small airfoils having a section of NACA 0012 and a chord of 0.5 inch. The generators were mounted perpendicular to the wing surface and projected 0.5 inch above the surface with centers at 2-inch intervals. The mean chord line of each generator was inclined at 15° to the normal to the 30-percent chord line of the wing. (See fig. 3.) Alternate generators were inclined toward the fuselage and the remaining ones were inclined away from the fuselage. The wing surface was smooth and the same section profile as existed with the generators removed was retained; the only protuberances,

as may be seen from the photographs of figures 4 and 5, were the individual generators.

Instrumentation

Standard NACA recording instruments were used to measure altitude, airspeed, accelerations, rolling velocity, control-surface positions, and control forces. Chordwise surface pressures over the upper and lower surfaces of one span station of the right wing (fig. 3) were measured with an NACA recording manometer.

Procedure

The first flight was made with the vortex generators extending spanwise from approximately the midflap to the midaileron station. A lift-off and landing was made followed by a flight to altitude to determine, primarily, the low-speed handling characteristics of the airplane with the generators installed. The second flight was made with generators extending from the midflap span station to the tip. The third flight was made with generators extending across the complete span.

The flights at altitude consisted, in general, of low-speed stalls, pull-ups through the buffet region at Mach numbers up to approximately 0.89, and abrupt aileron rolls at Mach numbers above 0.70. The flight conditions were repeated with generators removed.

The data presented herein are for the full-span configuration except that the lateral-control effectiveness data are for the configuration of the second flight and the drag data are for all configurations.

RESULTS AND DISCUSSION

The effect of wing vortex generators of one specific size, type, and location on the pressure distribution is presented and discussed. This information is followed by a presentation and discussion of the effect of wing vortex generators on the over-all airplane measurements of buffeting, lateral unsteadiness, trim changes, lateral-control effectiveness and drag.

Wing chordwise pressure distribution.- The chordwise pressure distributions over the upper surface of the wing test station for the basic configuration and the full-span generator configuration are given in

figure 6 for a Mach number range of 0.72 to 0.89 selected for a normal-force coefficient of approximately 0.25 ± 0.05 . As may be noted in figure 6, the distributions are similar up to a Mach number of 0.85 except for the regions where the generators are installed. In these regions the pressures at the leading edge of the generators are slightly more positive with a resulting greater negative pressure for 10 to 15 percent of the chord aft of the generators than without the generators. At a Mach number of 0.82 both distributions show a compression shock located at approximately 55-percent-chord location and neither distribution indicates separation over the rear portion of the section. At a Mach number of 0.85 the shock has moved rearward to approximately 60-percent chord with no indication of separated flow to the rear of the shock. As the Mach number is increased to 0.88 and 0.89 the distributions for the basic configuration show the shock to be moving between the 50- and 60-percent-chord location with a region of separation aft of the shock that is indicated to be expanding rapidly. The distributions with generators show that the shock continues to move rearward with no separation occurring.

The effect on the upper-surface pressure distribution of increasing the normal-force coefficient for both configurations is shown in figure 7 for Mach numbers of 0.85 to 0.88. For a Mach number of 0.85 at a normal-force coefficient of 0.20, there is no indication of separated flow aft of the shock, and the distributions are similar for both configurations. As the normal-force coefficient is increased to 0.75, the distribution for the basic configuration shows the shock has moved forward to approximately the 20-percent-chord location and that separated flow exists over the rear 70 to 80 percent of the chord. With generators, the shock has moved forward only about 10 percent of the chord with a less adverse pressure recovery over the rear portion of the section. It is indicated, however, that with generators for this normal-force-coefficient separation has started to occur over the rear portion of the chord. At a normal-force coefficient of 0.82, which is the airplane maximum lift for a Mach number of 0.85, the distributions show some similarity and the benefit of the generators, as might be expected, has decreased. For a Mach number of 0.88 and to the highest normal-force coefficient tested ($C_{NA} = 0.44$), it is shown that use of the generators resulted in a reduction of the separated region over the section.

Lower-surface distributions are shown in figure 6 for Mach numbers of 0.72 and 0.89 and in figure 7 for normal-force coefficients of 0.82 and 0.29. At all Mach numbers and normal-force coefficients investigated no appreciable change was observed in the lower-surface distributions due to the vortex generators.

Buffeting characteristics.- The D-558-I airplane buffet boundary presented in figure 8 was established by the Mach number and the corresponding airplane normal-force coefficient at which the first indication of buffeting occurred. The information was determined from the response of a standard NACA normal accelerometer to an airplane disturbance and correlated with the other instrumentation measuring various quantities in the airplane. The test data obtained with and without generators are noted. As may be seen, the boundaries for the two configurations are similar except at the highest Mach number tested where it is indicated that the boundary occurs at a higher Mach number by use of the generators. Measured chordwise pressure distributions corresponding to flight conditions where buffeting first occurred are presented in figure 9. The distributions are presented for selected conditions on the buffet boundary and are identified in relation to figure 8, that is, region I shows flight conditions where buffeting started for both configurations; region II shows flight conditions where buffeting occurred for the basic configuration, but where no occurrence of buffeting with generators installed is evident; region III shows flight conditions where buffeting occurred with generators installed.

No measurements were made to determine the effect of generators on the buffeting intensities. It is expected, however, that reductions in separated regions by use of the generators would result in a reduction in buffeting intensities. The pilot reported that, during flights made into the buffet region below maximum normal-force coefficients, the buffeting intensities were appreciably reduced with the generators installed. No detrimental effects of the generators on the control characteristics of the airplane were reported by the pilot.

Lateral unsteadiness and trim change.- It is difficult in flying the D-558-I airplane to select the proper lateral trim to maintain precisely a "wings-level" flight condition and pilots have described the occurrence as attempting to balance the airplane on a pivot point. As the Mach number approaches a value of about 0.84 an abrupt lateral trim change has been experienced and has been termed by the pilots as "wing dropping."

The lateral unsteadiness and the trim change occurrences for the basic configuration are illustrated in the solid-line histories of measured quantities in figure 10 for level flight through the Mach number range from approximately 0.66 to 0.89. Measurements of rolling velocity and aileron force indicated that rolling oscillations existed up to a Mach number of about 0.84 with forces applied by the pilot in an irregular manner due to the irregular motions of the airplane. The magnitude of the applied forces are, however, within the values of the control friction and result in no movement of the controls. At a Mach number of 0.84 and a normal-force coefficient of approximately 0.2 (time, 24 sec), a lateral trim change, as indicated by a gradual

right roll, occurs with controls fixed. An abrupt roll to the left occurs when corrective total aileron angle of about 2° is applied for the right roll. At the maximum Mach number a total aileron angle of approximately 3° is required and the lateral unsteadiness is considerably increased over the low-speed value. The quantities measured during a repeat flight with vortex generators installed are included in figure 10 and are indicated by the dashed lines. As indicated, the lateral unsteadiness still exists at the lower Mach number with the vortex generators installed; however, the abrupt left roll has been delayed to a Mach number of about 0.89 when the airplane normal-force coefficient is equal to 0.35. It is indicated that the difficulty of maintaining wings-level flight after the abrupt roll still exists, as did the difficulty in the case with the basic configuration.

Lateral-control effectiveness.- A loss in lateral-control effectiveness for the D-558-I airplane without generators has been indicated at Mach numbers greater than approximately 0.86 as shown in figure 11. Data were obtained with the vortex generators installed from the midflap span station to the tip station of the wing, but only to a Mach number of 0.84 and, as might be expected from an inspection of the pressure-distribution measurements, no beneficial effects from the generators result at these Mach numbers. If it is assumed that the loss in lateral-control effectiveness results from the development of a region of separated flow over the aileron, it is indicated from the pressure distributions (fig. 6) that for Mach numbers greater than 0.88 the generators might reduce the loss in effectiveness.

Longitudinal trim changes.- The variation of the wing-section pitching moment with Mach number for the basic and full-span generator configurations, as determined by integration of the chordwise pressure distributions, is shown in figure 12. Also included in figure 12 is the variation of the elevator angle required for trim for a given stabilizer incidence. The data are for a normal-force coefficient corresponding to 1g flight. It is indicated that no large changes in the wing-section pitching moment occurred because of the installation of the generators, and the longitudinal trim data indicate that no appreciable changes in the downwash resulted from the installation.

Drag.- The comparison of the measured airplane total drag variation with Mach number for all configurations at a normal-force coefficient of approximately 0.25 is presented in figure 13. It is evident from figure 13 that the use of the generators resulted in an increase in drag. Because of the scatter of the data, however, little can be concluded regarding the effect of spanwise location of the generators on the drag.

CONCLUDING REMARKS

The results indicated that vortex generators of a specific size and type located along the 30-percent wing chord line had the following effects on the handling and buffeting characteristics of the D-558-I airplane:

1. There was a reduction of separated regions over the wing at Mach numbers greater than 0.85 for level-flight normal-force coefficients. At higher normal-force coefficients and Mach numbers greater than 0.85, regions of separation and forward movement of the shock were reduced.

2. The buffet boundary and wing-dropping tendency were delayed by approximately 0.05 in Mach number at level-flight normal-force coefficients ($C_{N_A} = 0.25$); however, no changes in the small-amplitude lateral oscillations could be detected.

3. Buffeting intensities, as reported by the pilot, were appreciably reduced during flight penetrating the buffet region for lift coefficients below the stall.

4. No detrimental effects on the longitudinal or lateral control were encountered for the conditions investigated.

5. The drag of the airplane was increased.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va.

REFERENCES

1. Donaldson, Coleman duP.: Investigation of a Simple Device for Preventing Separation Due to Shock and Boundary-Layer Interaction. NACA RM L50B02a, 1950.
2. Barlow, William H., and Lilly, Howard C.: Stability Results Obtained with Douglas D-558-I Airplane (BuAero No. 37971) in Flight up to a Mach Number of 0.89. NACA RM L8K03, 1948.

TABLE I

PHYSICAL CHARACTERISTICS OF DOUGLAS D-558-I AIRPLANE

Wing:

Area, sq ft	150.7
Span, ft	25
Taper ratio	0.54
Aspect ratio	4.17
Root section	NACA 65-110
Tip section	NACA 65-110
Sweepback of 50-percent-chord line	0
Geometric dihedral, deg	4.0
Incidence at root chord, deg	2.0
Geometric twist	0
Mean aerodynamic chord, ft	6.21

Ailerons:

Area aft of hinge line (both ailerons), sq ft	7.94
Mean aerodynamic chord, ft	0.772
Span (one side), ft	5.19
Hinge-line location (percent c_w)	85

Horizontal tail:

Airfoil section	NACA 65-008
Area, sq ft	35.98
Span, ft	12.25
Aspect ratio	4.17
Taper ratio	0.55
Tail length, from 0.25 M.A.C. to elevator hinge line, ft	16.34

Elevators:

Area aft of hinge line (both sides), sq ft	8.6
Span (one side), ft	5.91
Hinge location, percent horizontal-tail chord	75
Mean aerodynamic chord, ft	0.75

Vertical tail surface:

Area, sq ft	25.68
Span, ft	5.55
Aspect ratio	1.20
Taper ratio	0.56
Fin offset	0
Tail length, from 0.25 M.A.C. to rudder hinge line, ft	17.38
Dorsal-fin area, sq ft	9.08



TABLE I

PHYSICAL CHARACTERISTICS OF DOUGLAS D-558-I AIRPLANE - Concluded

Rudder:

Area aft of hinge line, sq ft	7.92
Span, ft	5.67
Mean aerodynamic chord, ft	1.44

Fuselage:

Fuselage length, ft	35.04
Fuselage depth (maximum), ft	4.0
Fuselage width (maximum), ft	4.0

Load condition:

Airplane weight (full fuel without tip tanks) lb	10,610
Center of gravity, percent mean aerodynamic chord	23.34
Negligible movement of the c.g. with fuel consumption.	



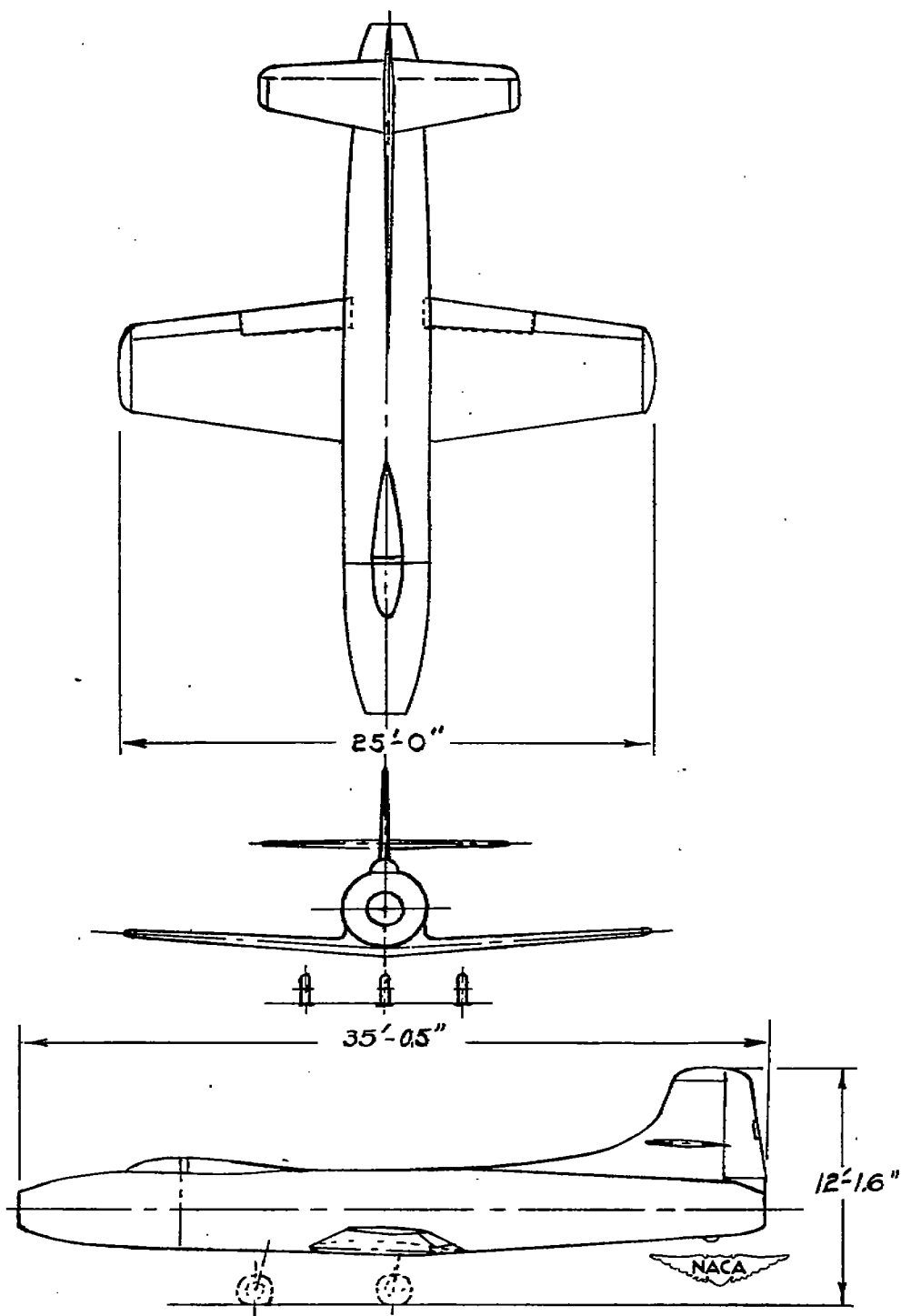


Figure 1.- Three-view drawing of the Douglas D-558-I airplane.

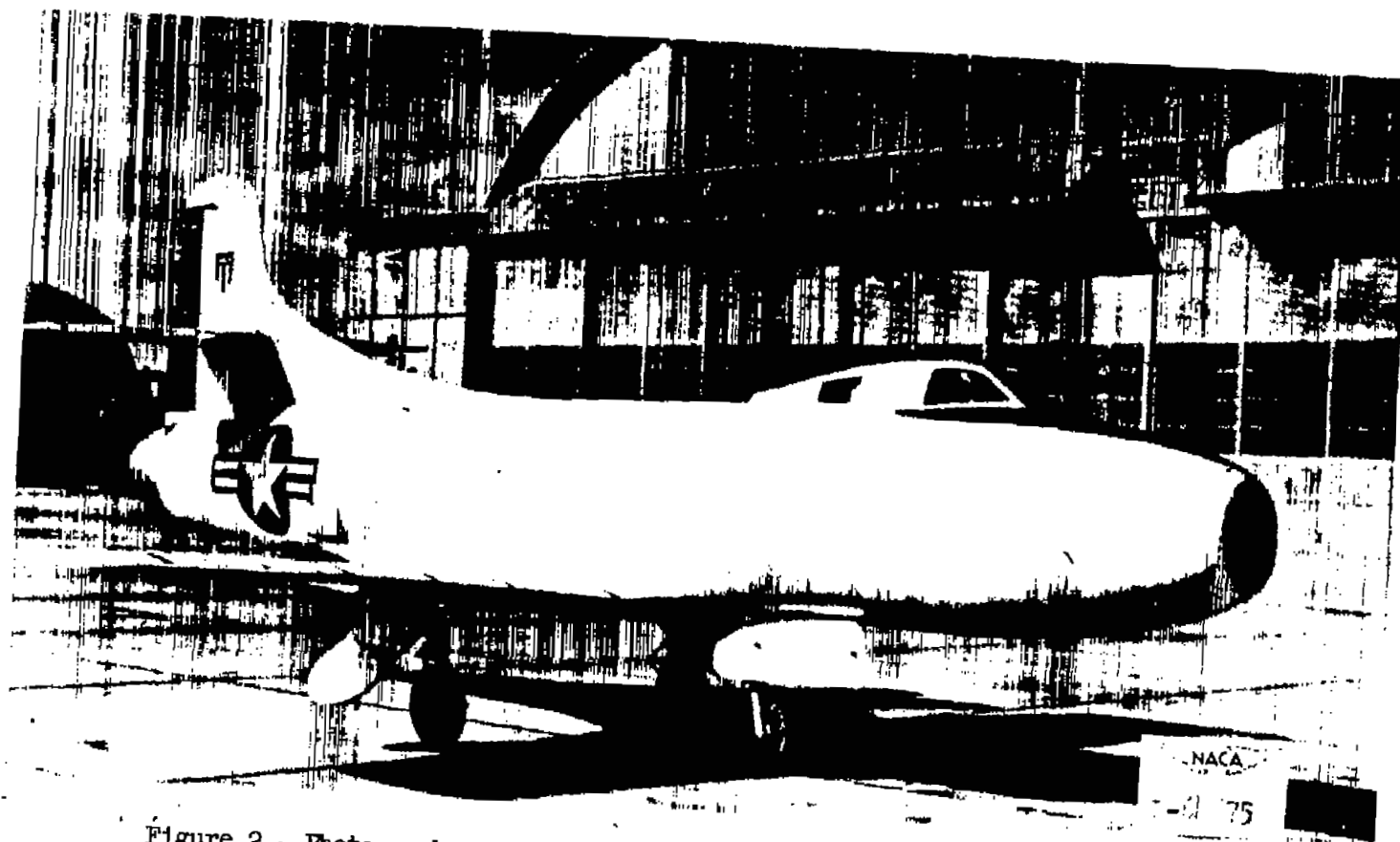


Figure 2.- Photograph of front quarter view of the Douglas D-558-I airplane.

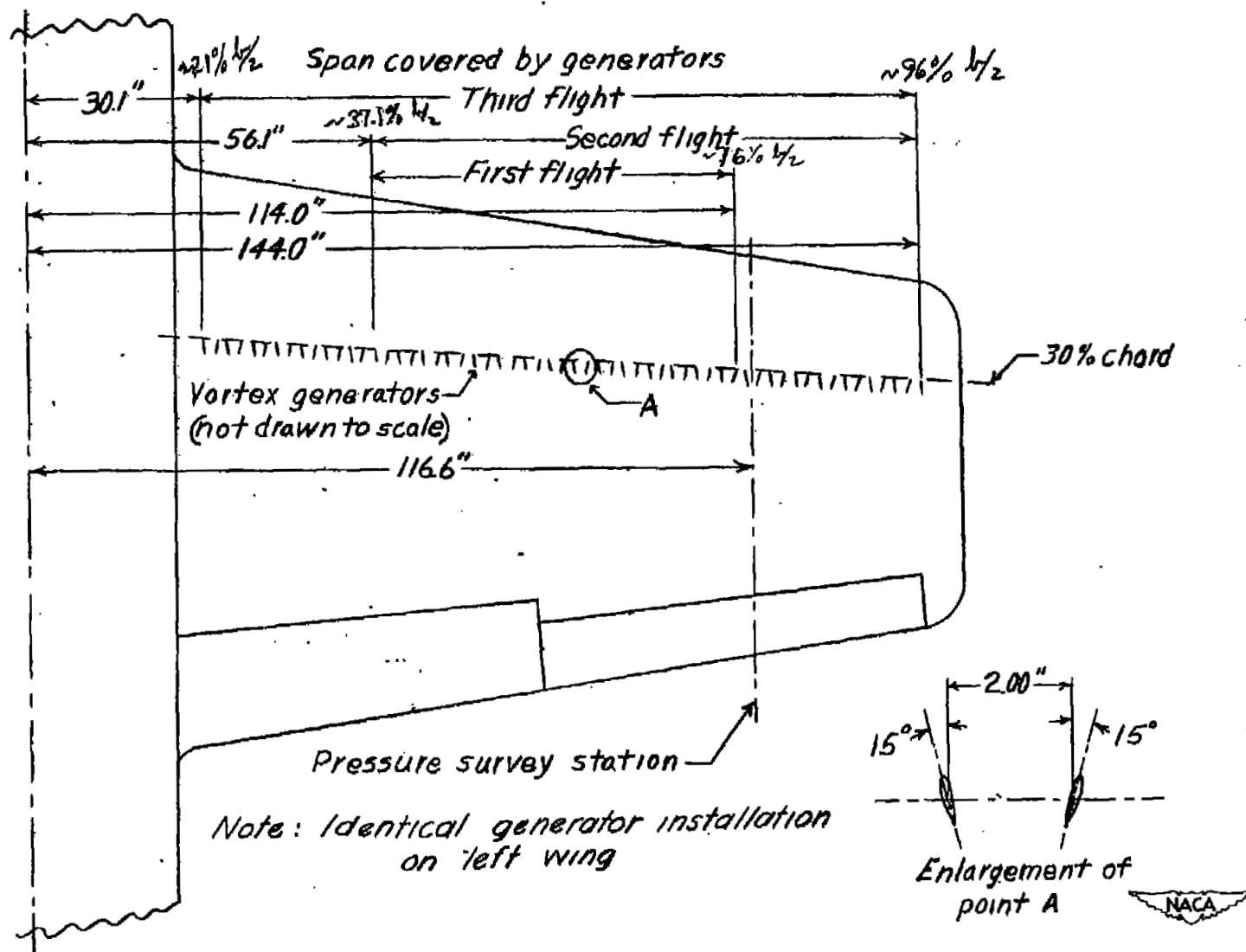


Figure 3.- Vortex-generator location on the D-558-I airplane.

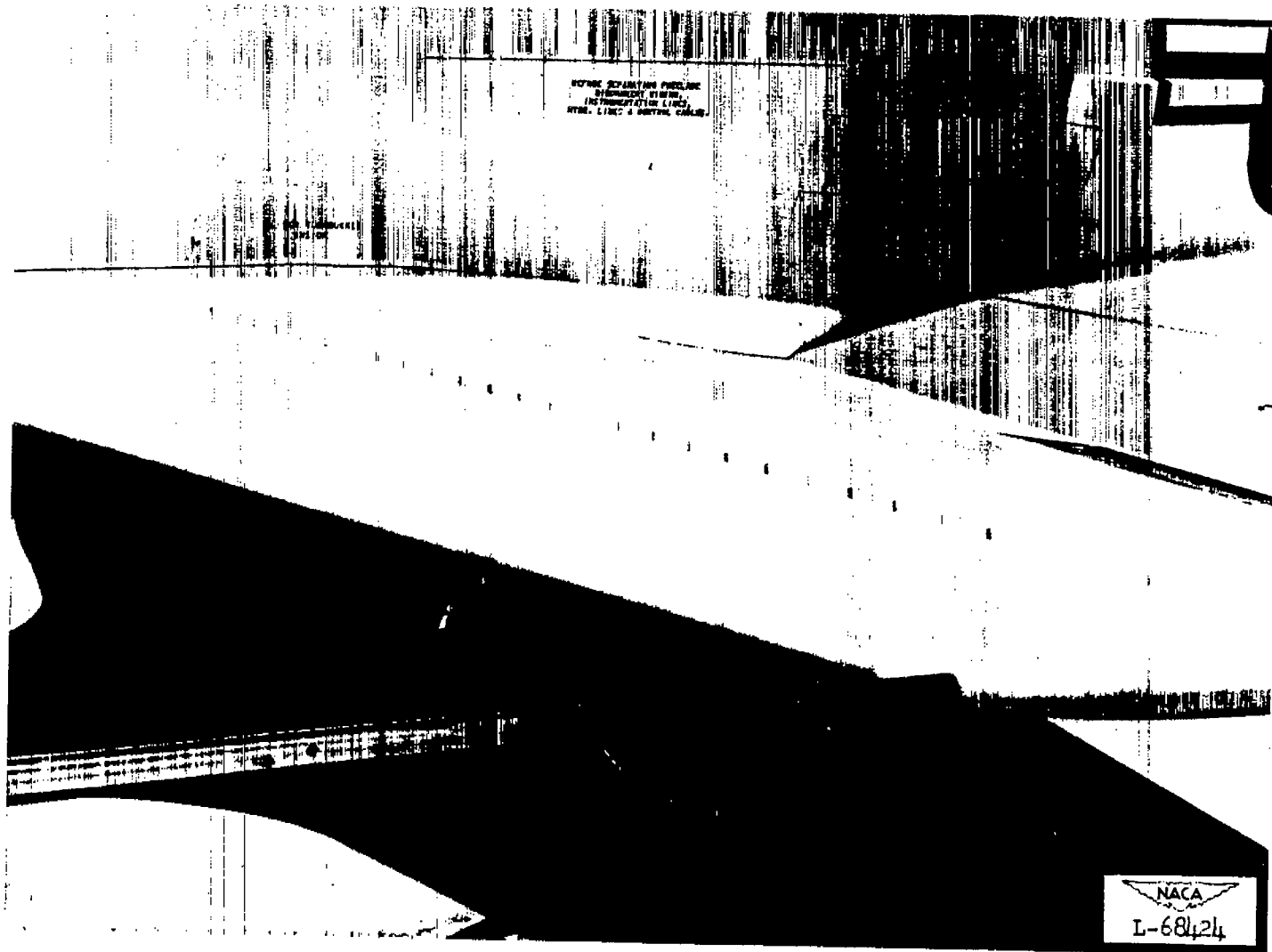


Figure 4.- Installation of vortex generators. D-558-I airplane.
(Full-span installation.)

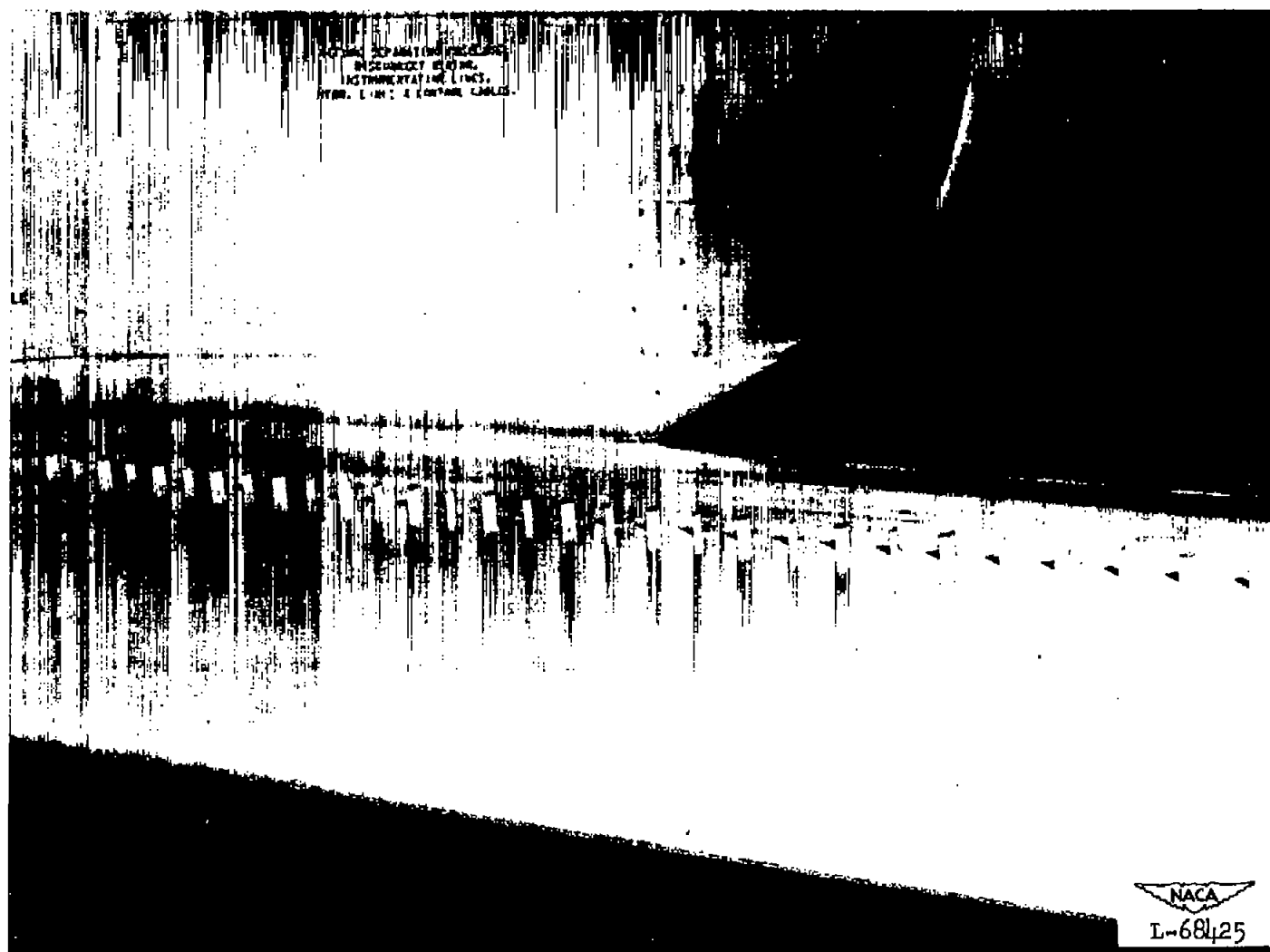


Figure 5.- Installation of vortex generators. D-558-I airplane. (Close-up of partial-span installation.)

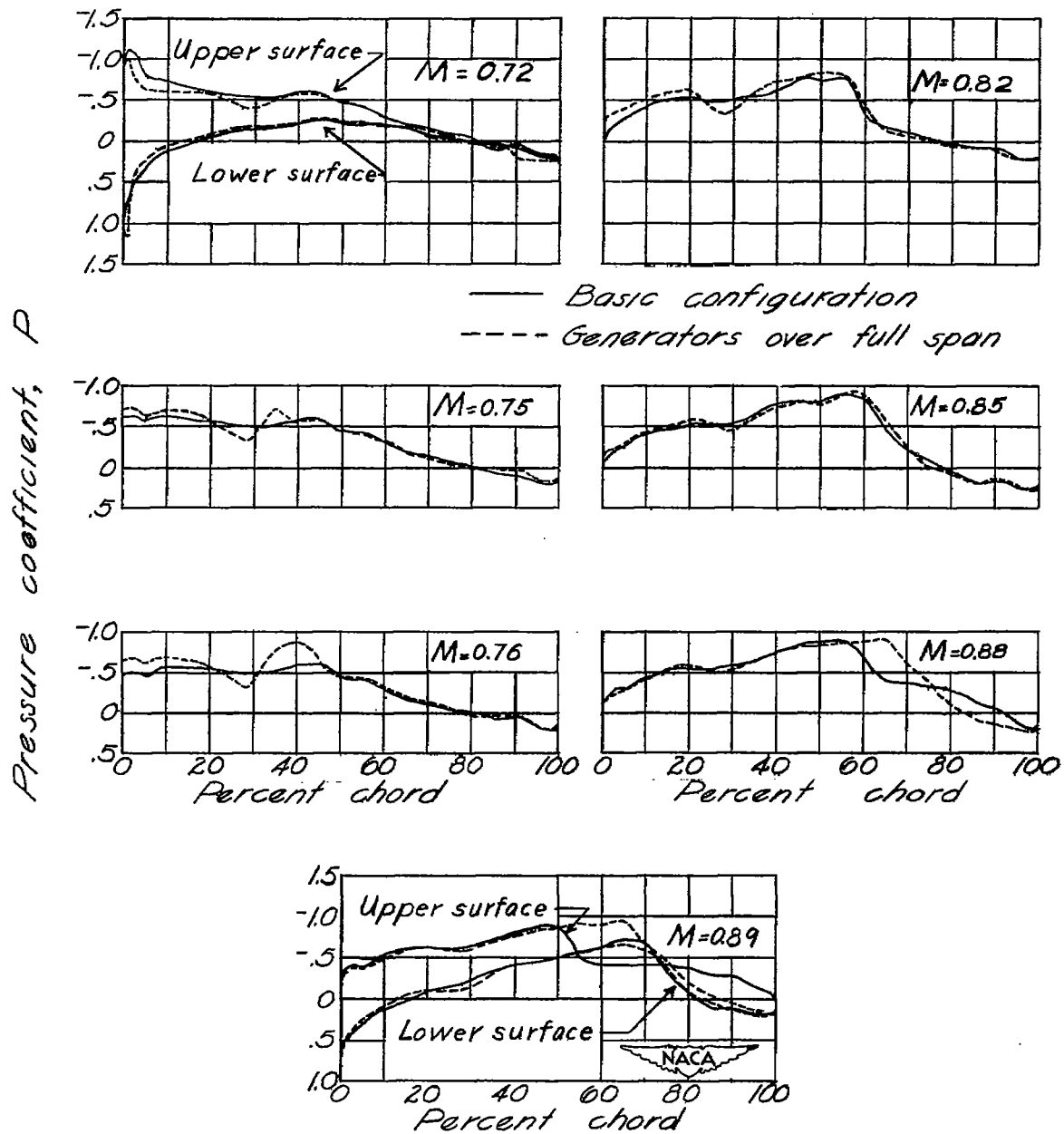


Figure 6.- Chordwise pressure distributions at various Mach numbers;
 $C_{NA} \approx 0.25$.

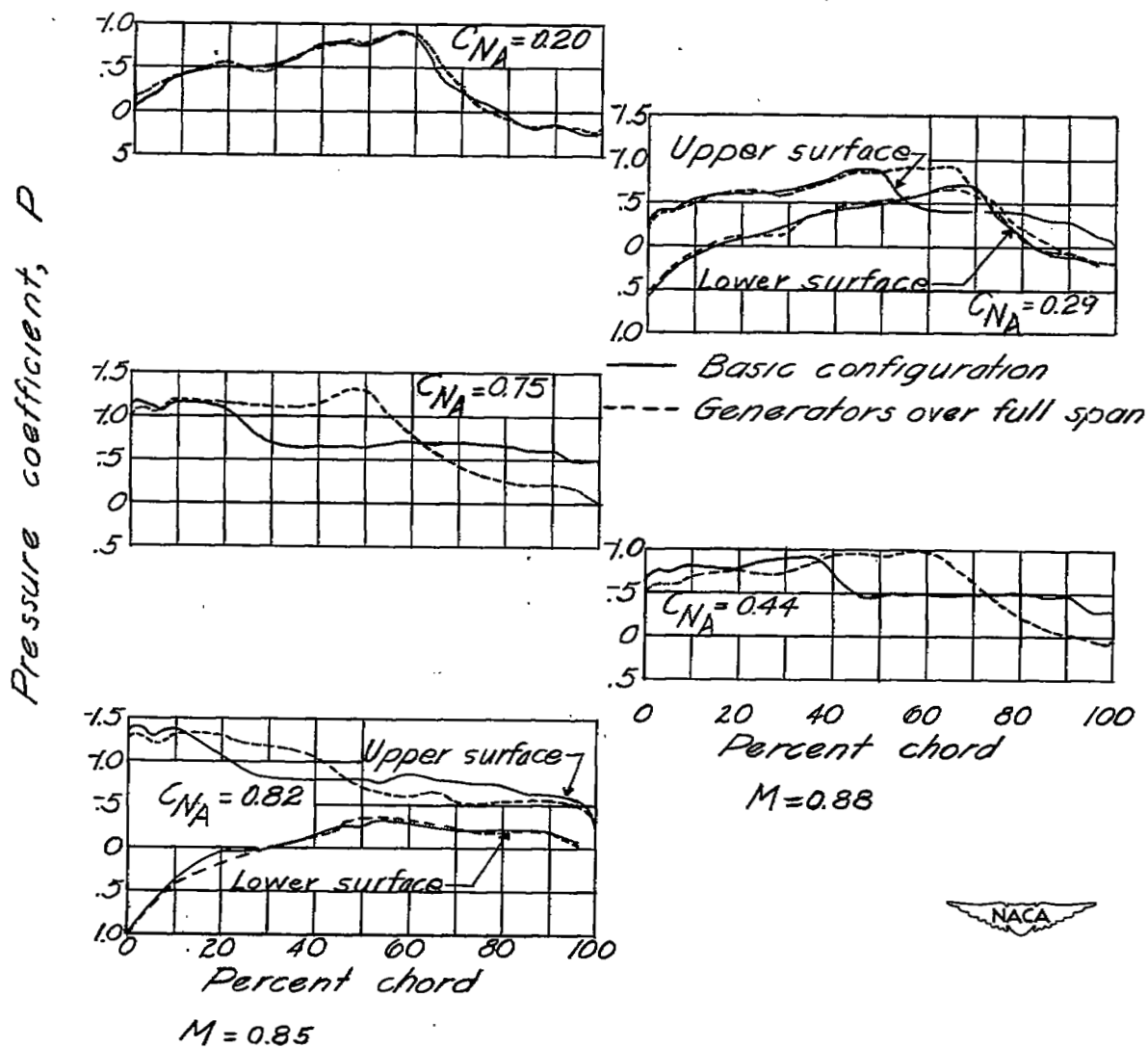


Figure 7.- Chordwise pressure distributions at various normal-force coefficients and Mach numbers.

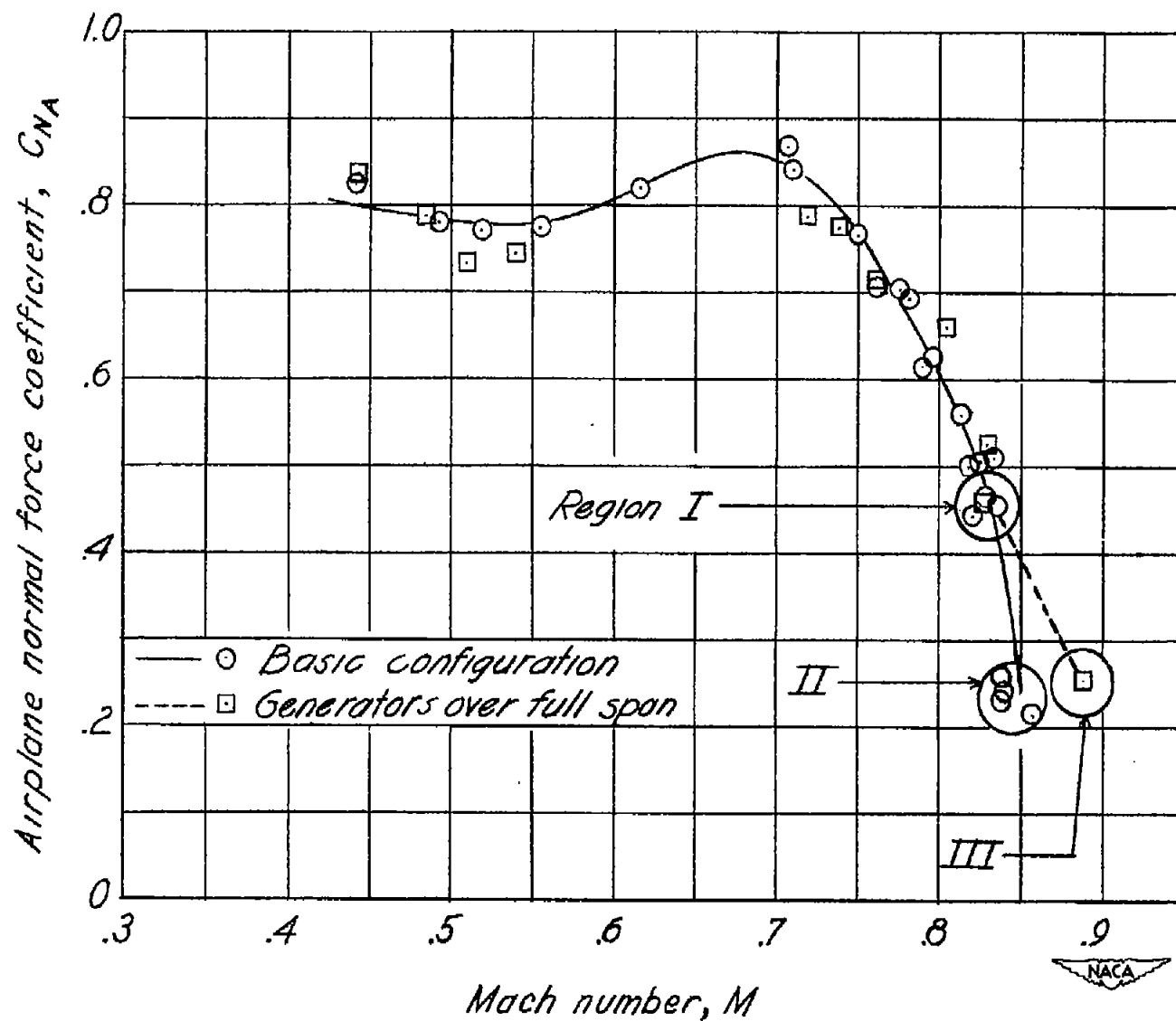


Figure 8.- Comparison of buffet boundaries with and without vortex generators.

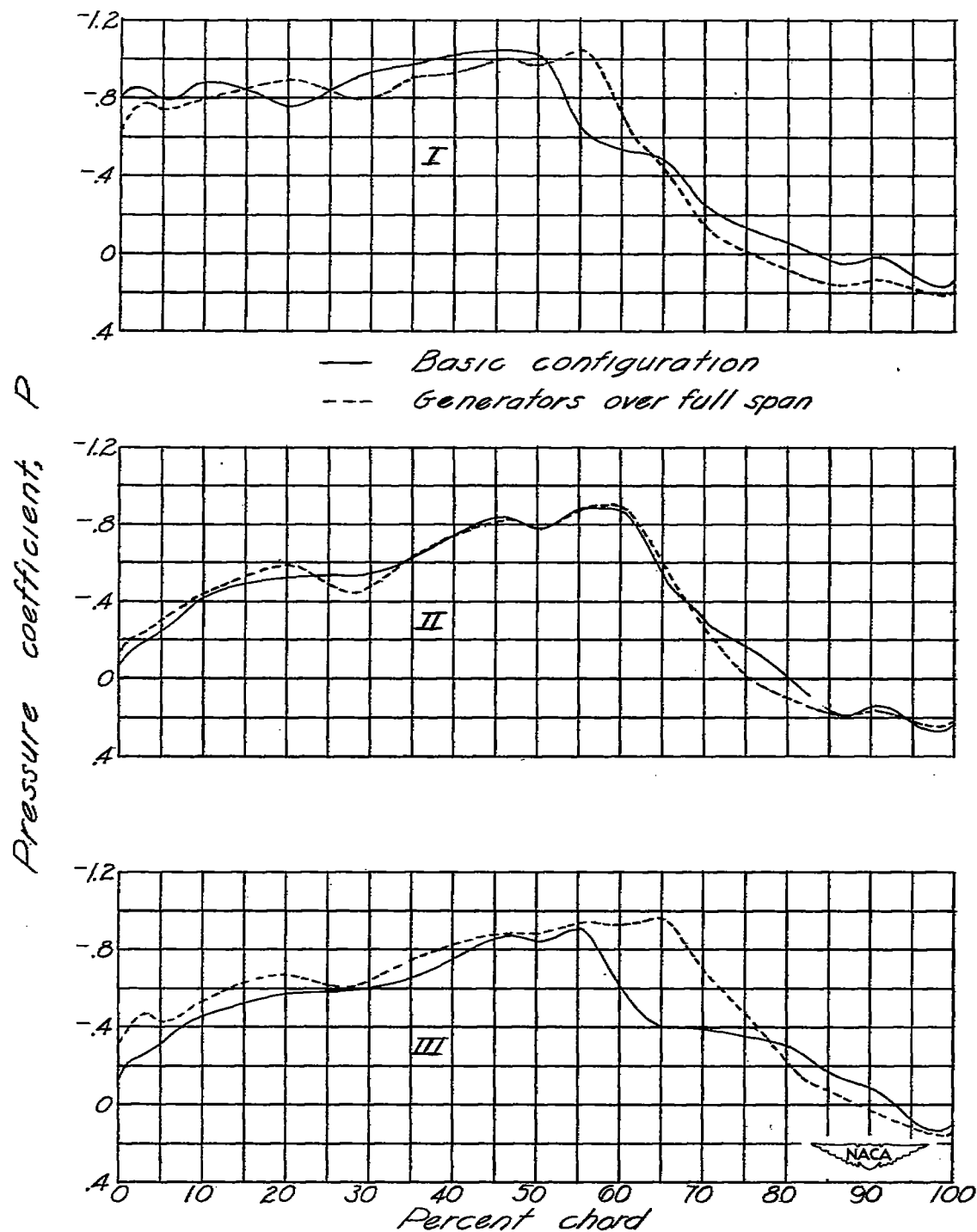


Figure 9.- Comparison of wing pressure distribution with and without vortex generators at conditions corresponding to the selected regions of the buffet boundary as shown in figure 8.

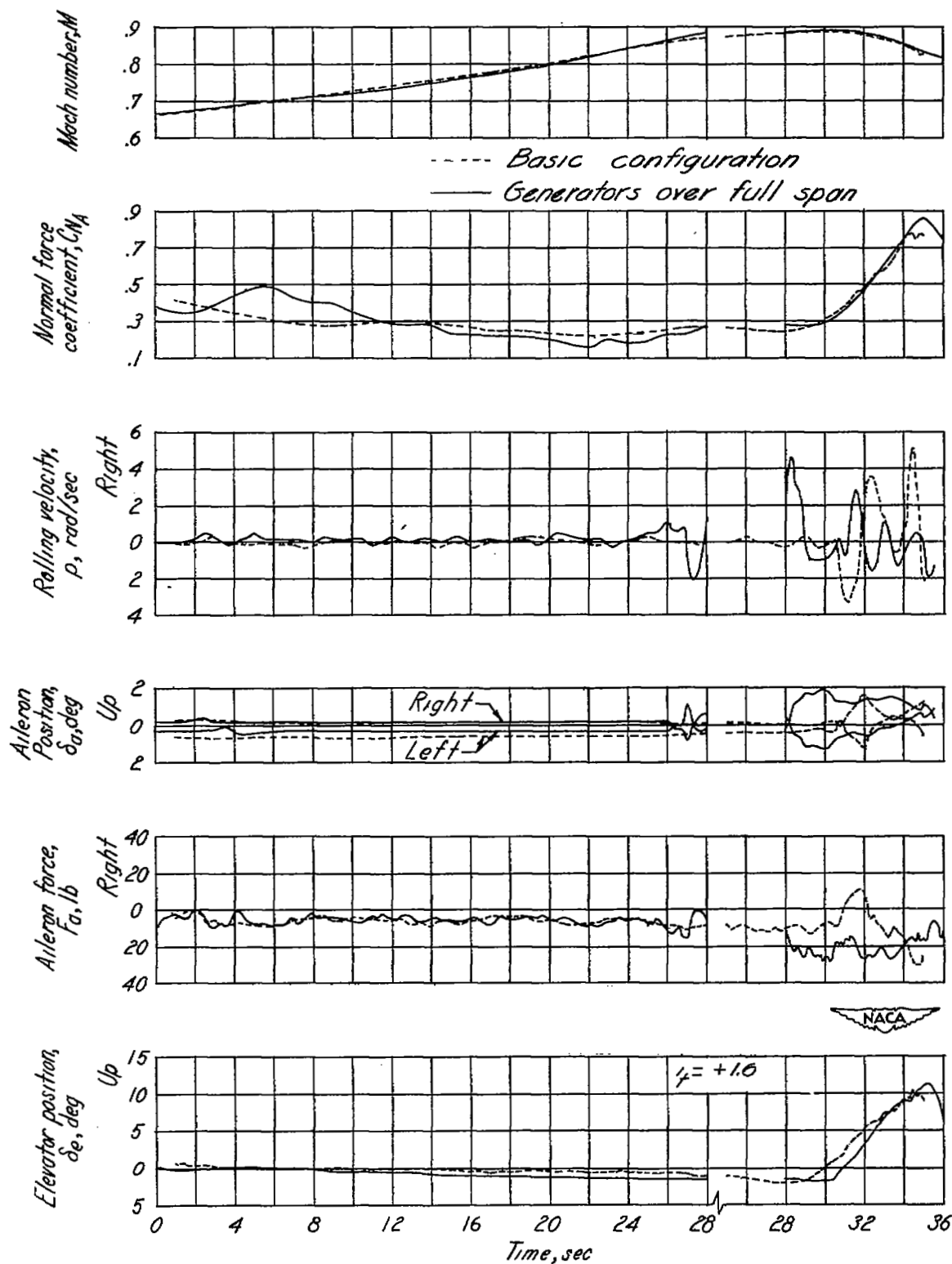


Figure 10.- Time histories of quantities measured during level flight and pull-up with and without vortex generators; altitude, 35,000 feet.

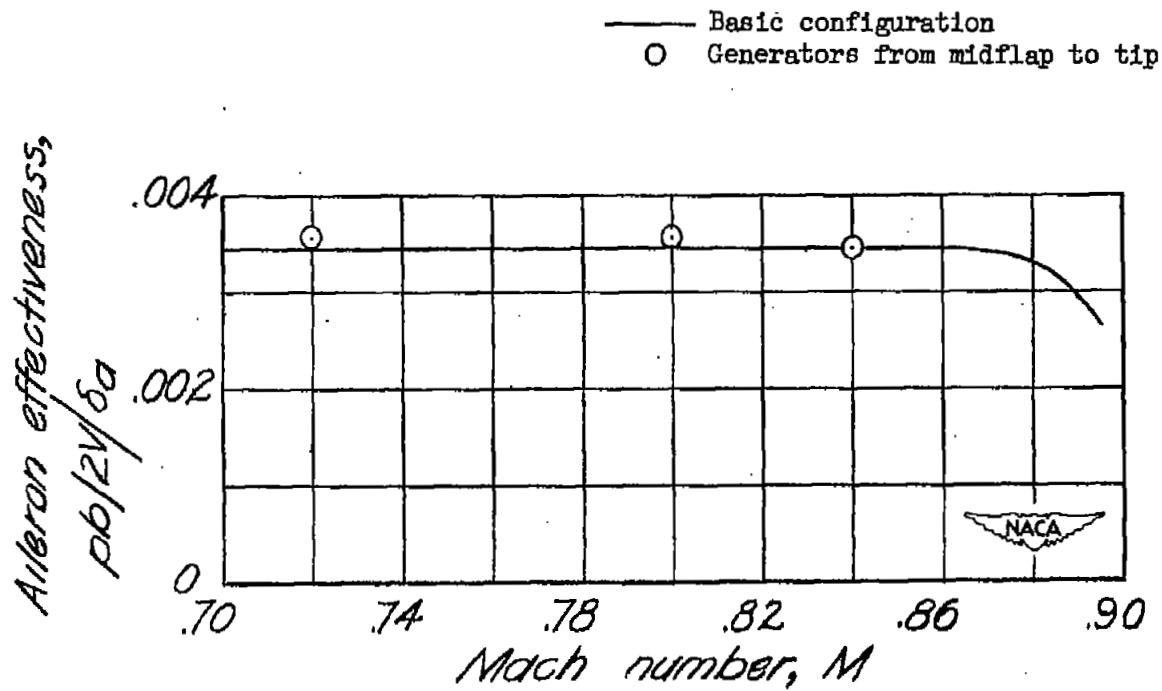
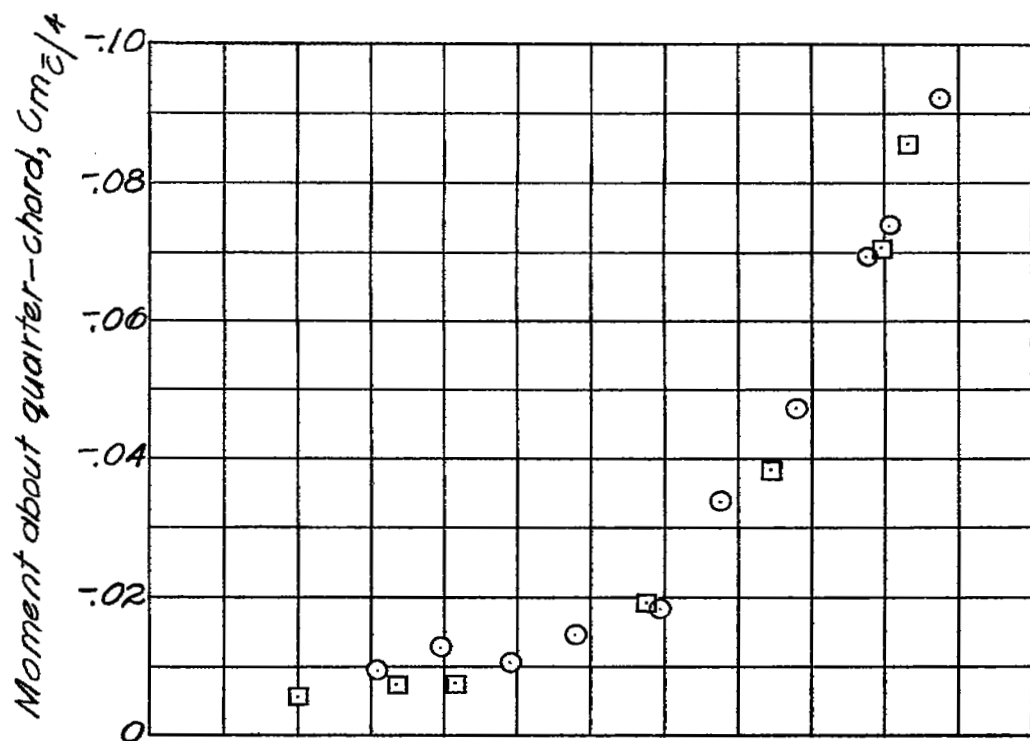


Figure 11.- Measurement of the lateral control effectiveness of the D-558-I airplane.



○ Basic configuration
 □ Generators over full span

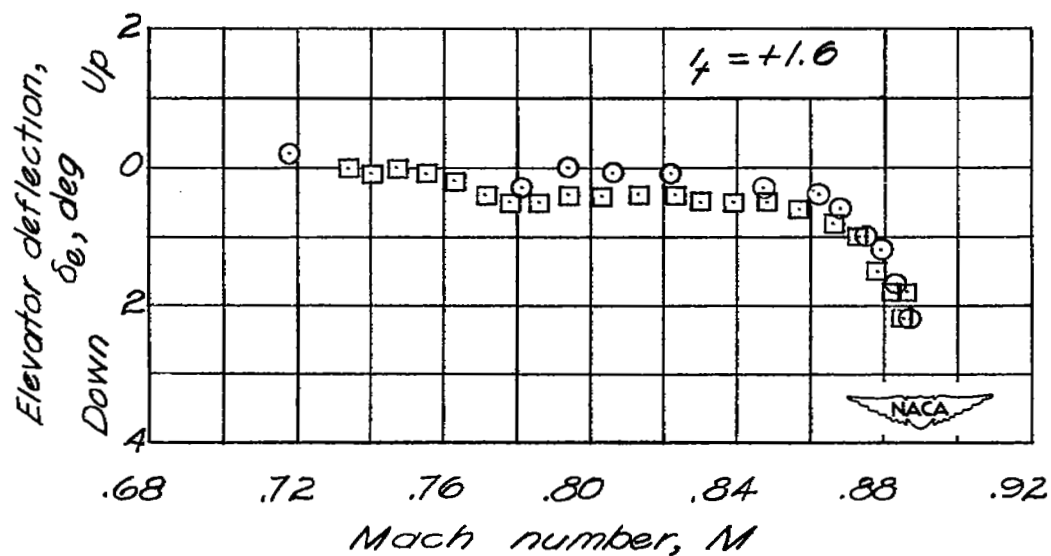


Figure 12.- Measurement of the wing pitching moment and longitudinal trim change of D-558-I airplane.

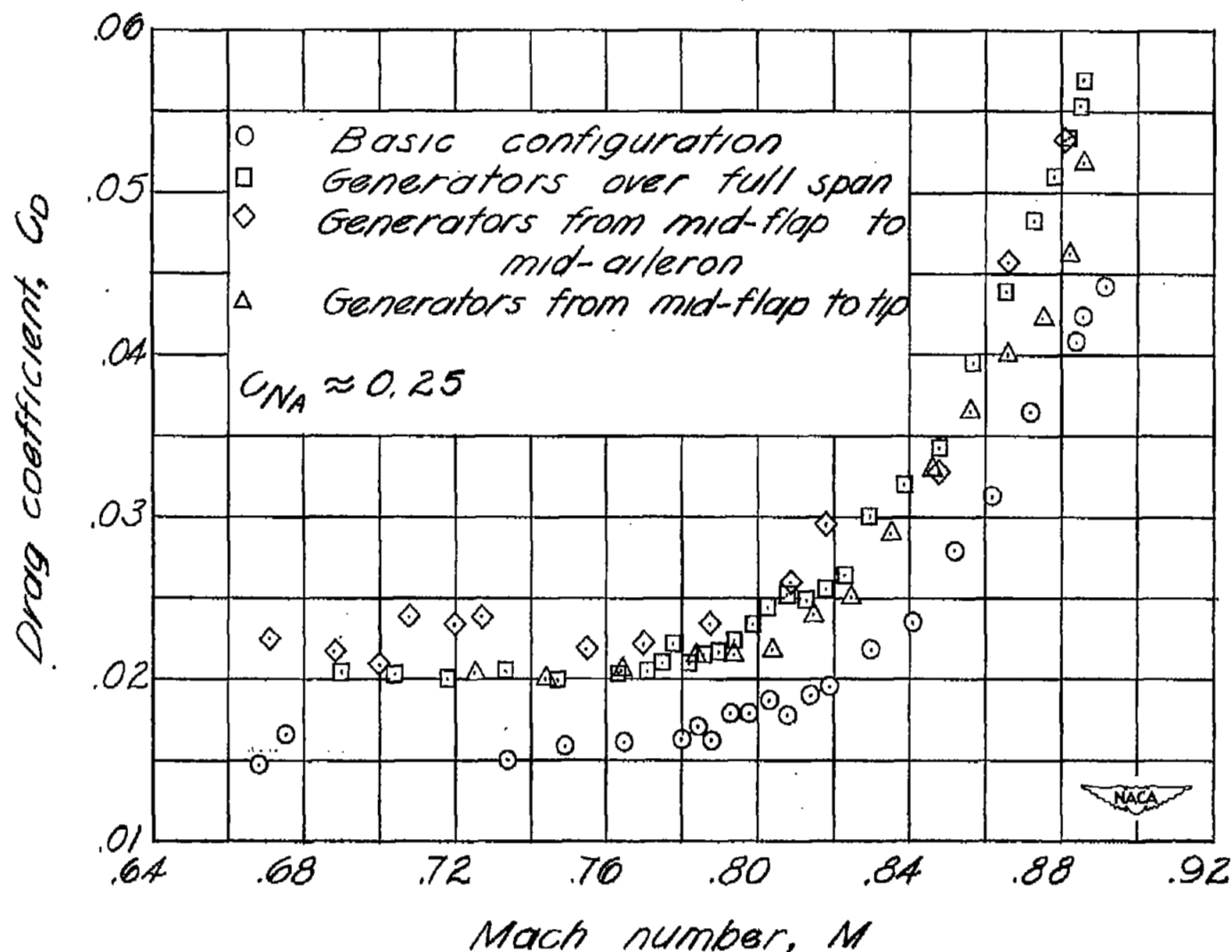


Figure 13.- Effect of vortex generators on drag coefficient during level flight.